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A Field Survey of Emissions From Aircraft Turbine Engines

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Nitrogen Oxides
Exhaust Emissions
Internal Combustion Engines
Probes
Sampling
Turbine Engines
Jet Engines
Chemical Analysis

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EPA (Environmental Protection Agency)
Environmental Protection Agency
Rolls-Royce Spey Engines
American Airlines
Society of Automotive Engineers
MBTH (3-Methyl-2-Benzothiazolone Hydrazone Hydrochloride)
3-Methyl-2-Benxothiazolone Hydrazone Hydrochloride

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A Field Survey of Emissions From Aircraft Turbine Engines

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UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

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II

A FIELD SURVEY OF EMISSIONS FROM AIRCRAFT TURBINE ENGINES

by

F. W. Cox,[1] F. W. Penn,[2] and J. O. Chase[3]

ABSTRACT

Exhaust emissions were measured from 25 aircraft turbine engines using Jet A fuel. Analytical apparatus, procedures, and results are described. Carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and aldehydes were measured at engine operating modes representing power levels used in airline operation. Carbon monoxide, hydrocarbon, and aldehyde emissions were highest at idle and lowest at takeoff; oxides of nitrogen were lowest at idle and highest at takeoff. Of the total oxides of nitrogen emitted, nitrogen dioxide constituted from 10 to 100 pct, depending on the exhaust gas temperature. Engines retrofitted with smoke-reducing burner cans produced less carbon monoxide, hydrocarbon, and aldehyde emissions, and slightly more oxides of nitrogen then engines with standard burner cans.

INTRODUCTION

Many investigators have reported studies of exhaust emitted by internal combustion engines, both spark ignition and compression ignition, but relatively little information is available on the emissions from aircraft turbine engines.

With the enactment of the Clean Air Act (4),[4] resulting in Federal standards for the reduction of air pollution from mobile sources, it became necessary to make a reliable assessment of current emission levels from a representative sampling of aircraft turbine engines in use in contemporary aircraft. To obtain this information, the Environmental Protection Agency (EPA) contracted with several groups to make onsite measurements at military and commercial overhaul facilities. The Bureau of Mines Bartlesville Energy Research Center (BERC), which had previously developed methodology (1), was one of the groups selected. Exhaust from several aircraft engines was analyzed for carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), total unburned hydrocarbons, and aldehydes.

---

[1] Research chemist.

[2] Mechanical engineer.

[3] Supervisory mechanical engineering technician.

[4] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

The Bureau obtained emission data on Pratt and Whitney JT8D and JT3D engines and Rolls-Royce Spey engines at the American Airlines overhaul facility in Tulsa, Okla., with American Airlines cooperation and support being provided as needed.

This report is a discussion of the sampling procedures and results obtained.

EXPERIMENTAL APPARATUS

Test Facility

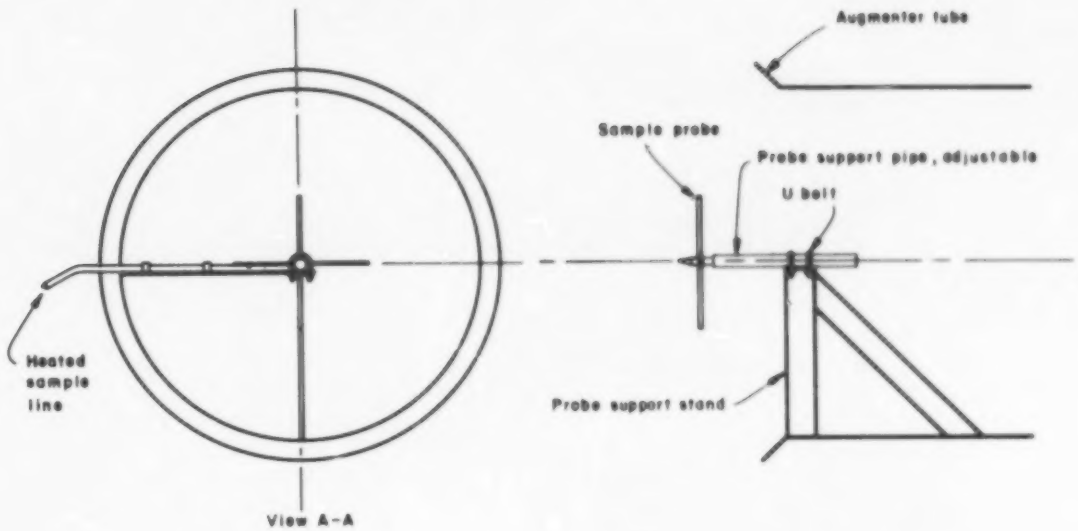
Two test cells at American Airlines, Tulsa, Okla., were utilized for the emission measurement program. They were located on opposite sides of and adjacent to the engine control room, where the instrumentation was installed next to the engine monitor and control equipment. The physical arrangement of the facility and equipment is shown in figure 1. Since the control room was compactly designed for test operator convenience, it was necessary to confine the analytical instruments to a small area. In compliance with this restriction, an instrument package requiring only 26 by 30 in of floor space was designed and constructed at the BERC. This package (fig. 2) contained the sample pump and all continuous sampling instruments except three strip-chart recorders.

Sample Probes and Support Stands

The probe designs were specified by the Environmental Protection Agency and the probes were supplied by Southwest Research Institute, San Antonio, Tex. Each probe consisted of four stainless-steel tubular arms welded to the wall of a cylindrical mixing chamber. The arms were positioned 90° apart in a single plane which formed a right angle with the mixing chamber wall. Three sampling holes in each arm were spaced so that sample was collected from four quadrants at the center of three equal annular areas of the tailpipe.

Probe failure was of considerable importance in terms of lost time, aborted tests, and collection of a representative exhaust sample. The major probe failures are exemplified in figure 3 (A-E). The final probe design (fig. 3F) proved adequate for JT8D testing but failed during the second JT3D test. None of the conventional probes could withstand the high exhaust gas pressures and temperatures generated by the Spey engines. To obtain emission data for the JT3D and Spey engines, a length of 1/4-in stainless-steel tubing was mounted on the leading edge of the vertical probe stand plate (fig. 1). The open end was capped and three 0.093-in diameter holes were drilled in the tubing at 2-in intervals below the augmenter centerline and facing the engine tailpipe.

Probe support stands were installed by American Airlines in the entrance of each exhaust augmenter tube (fig. 1). Each stand consisted of three 1/4-in by 4-in steel plates. The plates were bolted to angles which had been welded to the wall of the augmenter tube. At the common meeting point, the plates were bolted to a short tee section. Both of these probe stands failed and were modified by using thicker steel plates.



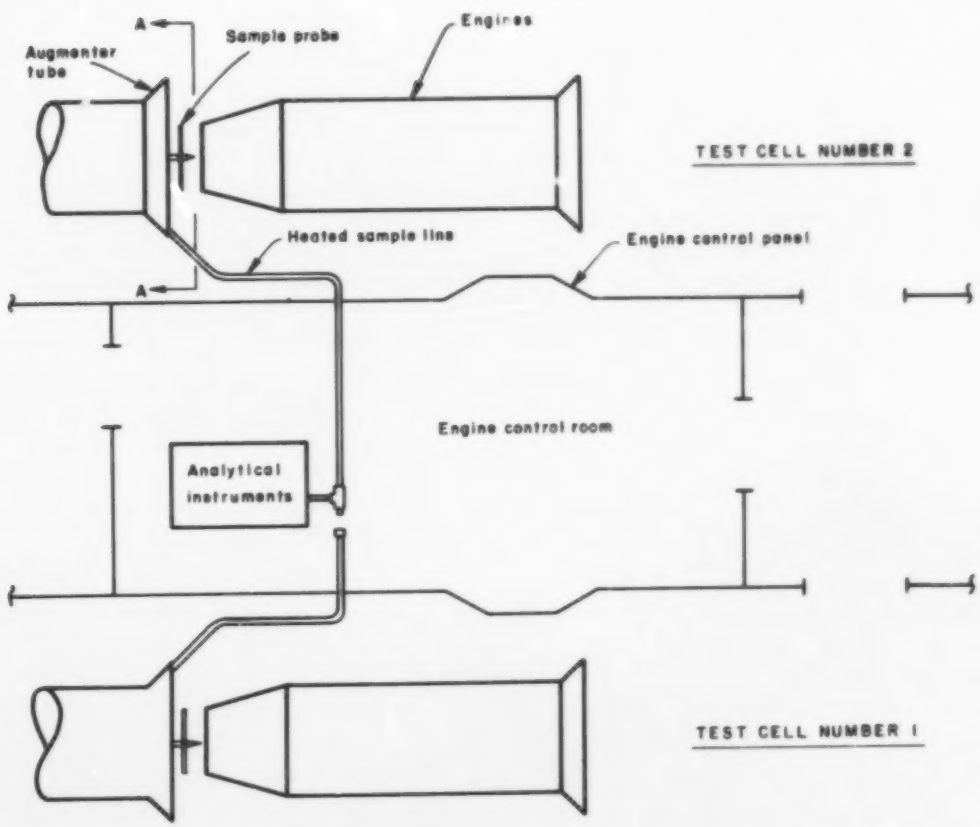


FIGURE 1. - Instrumentation in Test Facility.

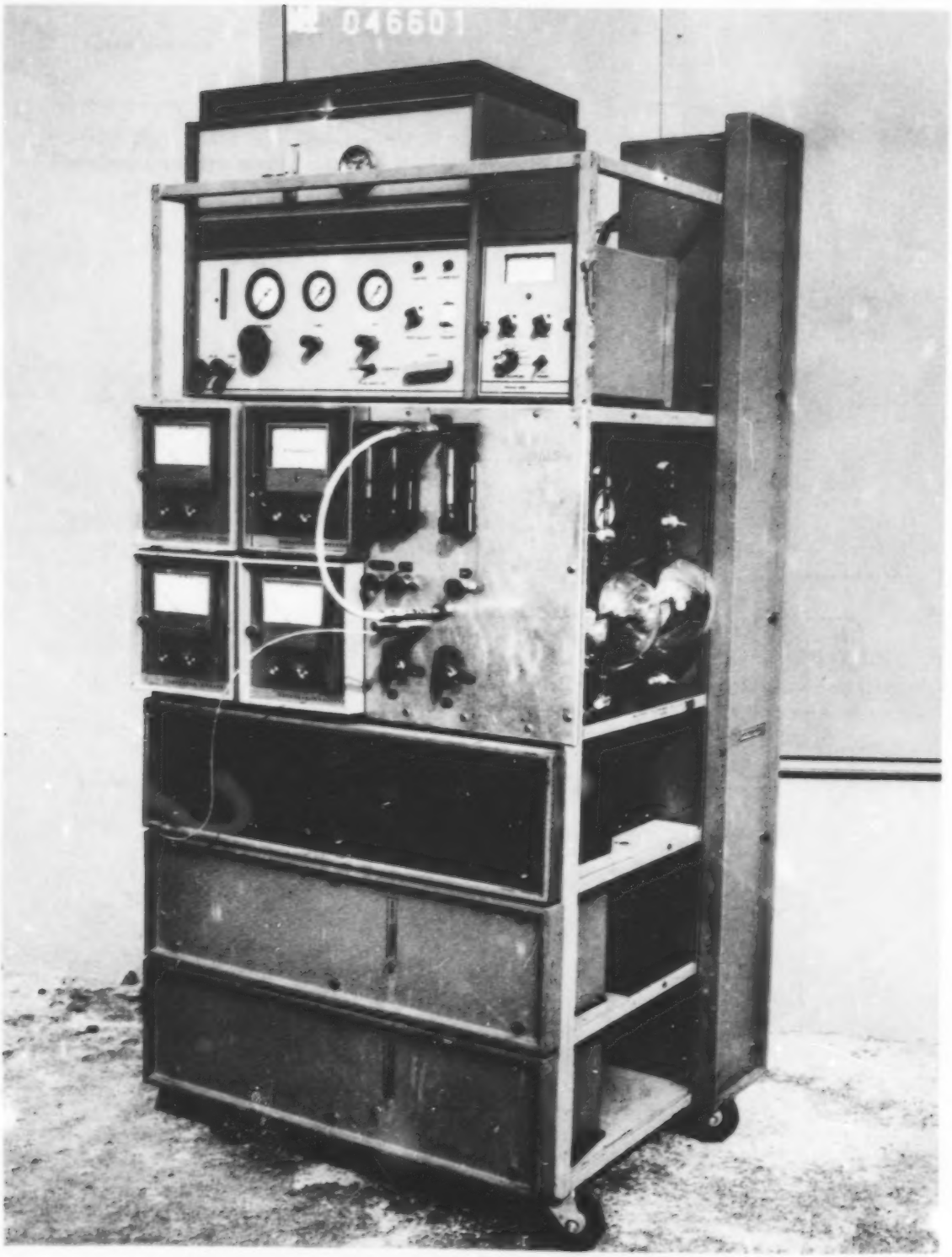


FIGURE 2. - Instrument Package for Emission Measurements.

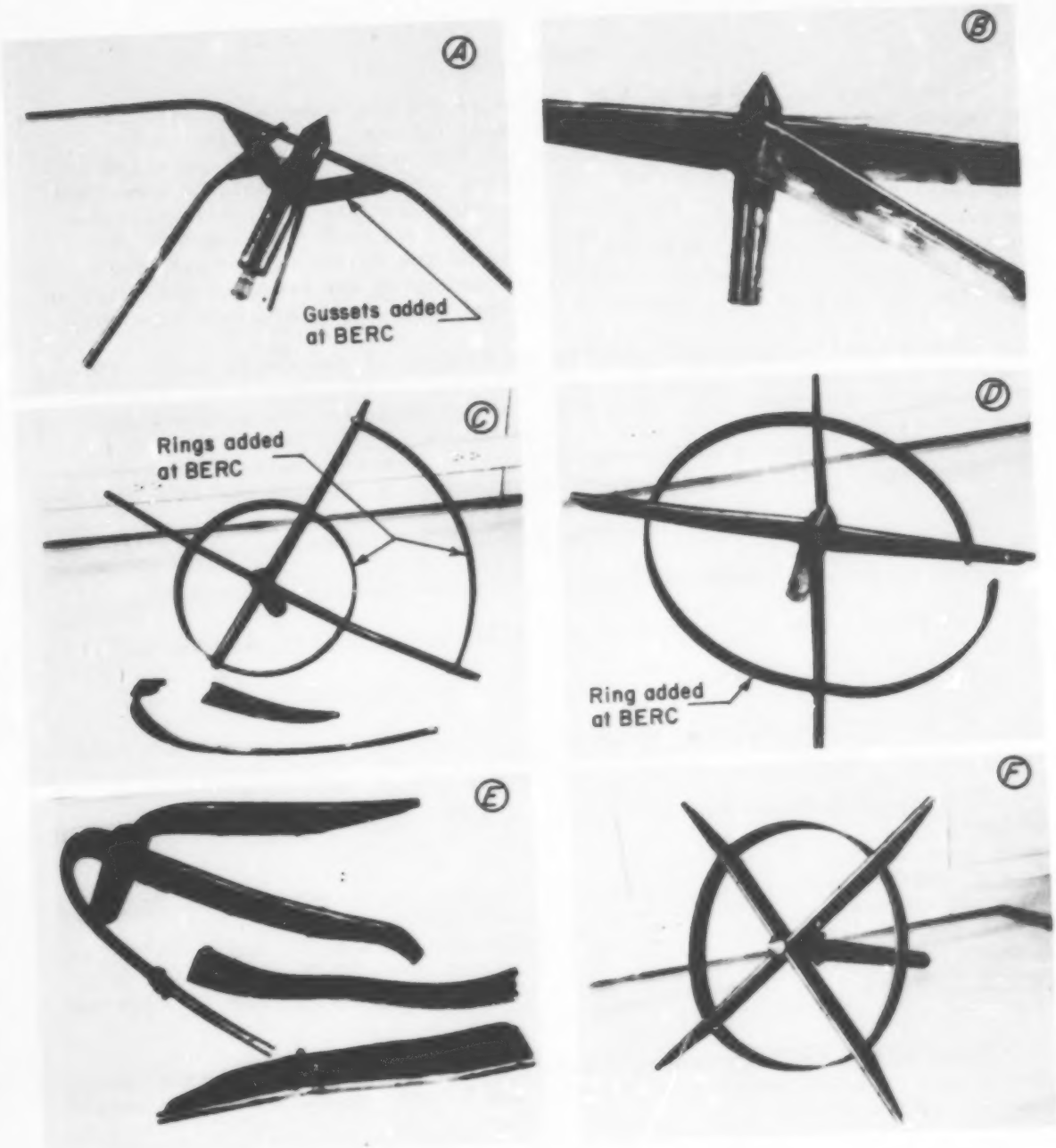


FIGURE 3. - Sample Probes Used in BERC Work. *A*, First design, failed behind the JT8D; *B*, third design (modified from second design), failed behind the JT8D; *C*, third design, failed behind the JT8D; *D*, third design, failed behind the JT3D; *E*, last design, failed behind the Spey; and *F*, last design, used only behind the JT8D engines.

Sample Lines

Sample was transferred from the probe to the instruments through 0.25-in OD (approximately 0.19-in ID) stainless-steel tubing. Sample lines were partially prefabricated in multiples of 2-1/2 ft prior to field installation. Each section was heated to a dull red so that contaminants could be vaporized and removed by nitrogen purge. Tubular heating elements (industrially manufactured in sections of 1/4-in ID by 2-1/2 ft) were then fitted end to end around the steel tubing. With the addition of thermocouples and swagelock fittings, installation became a matter of connecting the segments and wrapping the line with two to three layers of asbestos tape and an aluminum tape cover.

Despite the heavy insulation, the temperature of the sample line inside the test cell could not be maintained at the 150° C recommended by the Society of Automotive Engineers (3). Soon after engine ignition, the sample line temperature began to drop, reaching a low of about 115° C before the end of the test. The extent of temperature depression seemed to be somewhat related to engine speed, with maximum depression occurring at or near the takeoff mode.

Instrumentation

Gaseous exhaust components were measured continuously as follows:

1. Hydrocarbon (HC) by flame ionization detection (FID--Beckman 402[5]);

2. NO_2 by nondispersive ultraviolet (NDUV--Beckman 255); and

3. NO, CO, and CO_2 by nondispersive infrared (NDIR--Beckman 315A). The sum of NO and NO_2 will be referred to hereafter as NO_x.

Cell specifications and ranges for the NDUV and NDIR instruments were as follows:

Exhaust component	Instrument--cell size, in	Range 1	Range 2	Range 3
Nitrogen dioxide	NDUV, 13.5	0-100 ppm	-	-
Nitric oxide	[1]NDIR, 40.5	0-500 ppm	0-200 ppm	0-100 ppm
Carbon dioxide	NDIR, .125	0-10 pct	0-5 pct	0-2 pct
Carbon monoxide	[1]NDIR, 13.5	0-1,500 ppm	0-500 ppm	0-100 ppm

[1]Equipped with optical filters.

Three double-pen recorders were used to register instrument output--one recorder each for CO and CO_2, NO and NO_2, and HC and temperature of the sample line (or sample stream).

A schematic of the emission sampling system is shown in figure 4. Grab samples were taken for total aldehyde content and analyzed by the 3-methyl-2-benzothiazolinonehydrazone hydrochloride (MBTH) method (2).

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[5]Brand names are used in this report for identification only and their mention does not imply endorsement by the Bureau of Mines.

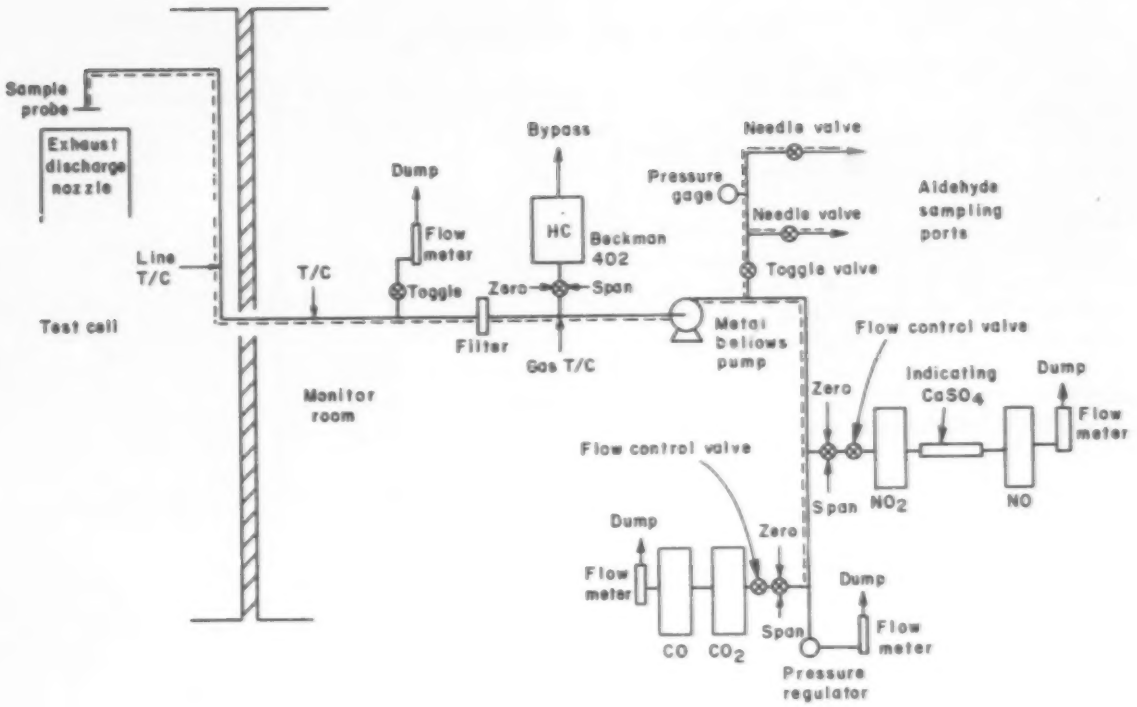

FIGURE 4. - Sampling System Flow Schematic.

EPA Reference Gases

The laboratories involved in the collection of aircraft emission baseline data analyzed a number of reference gases provided by the EPA. The purpose of the reference gas check was to determine whether major differences in analyses existed among the laboratories.

The Bureau analyzed seven EPA reference gases, and the results of these analyses are given in table 1. Note that the hydrocarbon level of the Bureau of Mines zero gas was about 4.8 ppmC higher than that of the EPA zero air. This means that the Bureau's hydrocarbon measurements shown in table 1 are 4.8 ppmC lower than they would have been had EPA zero air been used to zero the hydrocarbon analyzer. If this difference were applied to the Bureau of Mines hydrocarbon levels for EPA gases A-247 and SG-13359B, the deviations from EPA values then would be only -2.2 pct and +2.9 pct, respectively.

The hydrocarbon emission values contained in this report were not corrected for the hydrocarbons present in the Bureau's zero gas; therefore, these values could be as much as 4.8 ppmC low.

Fuel

Jet A fuel was used for all tests. Of the three fuels specified for use by American Airlines, Jet A is a relatively high flashpoint distillate of the kerosene type. Table 2 shows the fuel inspection data.

TABLE 1. - EPA[1] reference gases

EPA cylinder	Compound	Analyzed concentration		Percent deviation from EPA
		EPA	BuMines	
A-6775	Carbon monoxide....ppm..	82	95	+15.9
A-672	Carbon monoxide....ppm..	494	530	+7.3
A-672	Carbon dioxide.....pct..	1.57	1.59	+1.3
A-6741	Carbon dioxide.....pct..	4.22	4.22	0.0
A-2334	Nitric oxide.....ppm..	82.2	87.0	+5.8
SSB-162	Nitric oxide.....ppm..	21.0	18.0	-14.3
A-247	Hydrocarbon.....ppmC..	216.6	207	-4.4
SG-13359B	Hydrocarbon.....ppmC..	31.5	27.6	-12.4
	Air.....ppmC..	<0.1	-4.83	-

[1]Environmental Protection Agency, Ann Arbor, Mich.

TABLE 2. - Inspection data for Jet A fuel[1]

Gravity.....° API..	42.5
Flashpoint, tag closed cup.....° F..	125
Flashpoint, tag open cup.....° F..	144
Viscosity, kinematic.....cs at 100° F..	1.38
Distillation temperature, ° F:	
10-pct evaporated.....	367
50-pct evaporated.....	409
90-pct evaporated.....	471
End point.....	510
Distillation residue.....pct..	1.1
Distillation loss.....pct..	0.9

[1]American Society for Testing and Materials. Standard Methods of Test for Specifications for Aviation Turbine Fuels. D 1655 in 1970 Book of ASTM Standards: Part 17, Petroleum Products--Fuels, Solvents, Burner Fuel Oils, Lubricating Oils, Cutting Oils, Lubricating Greases, Hydraulic Fluids. Philadelphia, Pa., 1970, p. 582.

Engines

Emissions were measured from 25 engines: Three Pratt and Whitney JT3D, 18 Pratt and Whitney JT8D, and four Rolls-Royce Spey engines. The JT3D is a turbofan engine with external bypass, and the JT8D and Spey are turbofan engines with internal bypass systems. Of the 18 JT8D engines tested, 13 had been retrofitted with smoke-reducing burner cans and the remaining five JT8D engines as well as the JT3D and Spey engines were equipped with standard burner cans. Time in operation since overhaul varied from 0 to over 11,000 hr.

EXPERIMENTAL PROCEDURE

Analytical Procedure

The analytical procedure recommended by SAE Committee E-31,[6] and subsequently published (3), was followed as closely as practicable. The NDIR, NDUV, and FID analyzers were checked for zero and span prior to each test and for zero after each test, except when both test cells were utilized and a second test immediately followed the first. At times, field conditions made strict adherence to the recommended procedure impractical. Areas of departure from the SAE procedure were as follows:

1. Only one propane blend was used for daily span checks on the FID analyzer; this blend contained 432 ppmC.

2. Sample line temperature in the test cell could not be maintained at 150° C, as discussed previously.

3. For the JT3D and Spey engines, the distance between the probe stand and the tailpipe was too great to place the sample probe within one-tailpipe diameter of the exhaust exit plane.

4. Owing to probe failures, it was necessary in some cases to use sample probes other than those of conventional design.

Aldehyde analysis is not included in the SAE recommendations. For the work done at American Airlines, a flow-through method was used to collect duplicate aldehyde grab samples. First, two evacuated 2-liter, two-stopcock flasks (fig. 2) were filled with exhaust. Then the exit stopcocks were opened to allow exhaust to flow through the flasks for about 3 min. Condensation during the collection process was prevented by heating the flasks with a heat gun. After the flow-through period, the flasks were pressurized with exhaust to about 3 psig (enough to insure a slight positive pressure at room temperature). When the flasks had cooled to room temperature, one stopcock on each flask was opened to permit equilibration to atmospheric pressure and introduction of 10 ml of MBTH reagent solution. The reagent was added to the flasks with a hypodermic syringe through a 4-in needle. From this point, the method recommended by the Coordinating Research Council (2) was followed.

Emission Measurement

The modes of engine operation normally used by American Airlines for acceptance testing were utilized by the Bureau of Mines for emission measurements. Operating modes for Pratt and Whitney engines are idle, part power, cruise, maximum continuous, and takeoff. With the exception of part power, these modes represent power levels used for flight operations. The part-power mode is used in conjunction with idle to trim the Pratt and Whitney engines

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[6] R. W. Hurn (Chairman), Bureau of Mines; J. H. Elwood, Pratt and Whitney Aircraft Co.; R. C. Williamson, General Electric Co.; and Jack Vaught, General Motors Corp.

(adjust the throttle stops and linkage on the fuel control) so that throttle misalinement can be minimized when the engines are installed in multiengine aircraft. The modes used for testing Spey engines are idle, takeoff, and four intermediate-speed check points. The Spey engines are trimmed at idle and takeoff.

Although the sample lines from the probes to the instruments were approximately 35 ft long, the sample transport time was substantially less than 1 second. The toggle valve, just upstream from the particulate filter (fig. 4), was used to dump excess sample that tended to overpressurize the instruments at engine modes other than idle. This method of sample-volume control, rather than in-line valving, was chosen in order to permit the sample pump to deliver at the maximum rate. The pressure regulator, downstream from the CO_2 analyzer, served to pressurize the sample sufficiently to feed the instruments and aldehyde-sampling system.

CO, CO_2, NO, NO_2, and HC were monitored for the duration of each test, but emission levels were calculated from recorder deflections reached upon stabilization at each mode. During this stable period, aldehyde grab samples were taken.

All of the exhaust component values discussed except NO were obtained from wet measurements. The sample stream for NO measurement was first dried by a column (5/16-in ID by 18 in) of indicating calcium sulfate. The NO measurement was taken, then converted to a wet basis by the following calculation:

$$NO_{wet} \approx NO_{dry}\left(1 - \frac{Y}{100}\right)\left(1 - \frac{CO_2}{100}\right) - 0.25\ NO_2, \qquad (1)$$

in which Y = percent water in the intake air,

CO_2 = measured percent CO_2 in the wet exhaust,

NO_2 = measured ppm NO_2 in the wet exhaust,

NO_{dry} = measured ppm NO in the dry exhaust,

and $0.25\ NO_2$ = the fraction of NO_2 converted to NO by the calcium sulfate column (determined experimentally at the BERC).

RESULTS AND DISCUSSION

Emission baseline data for the individual tests are attached to this report as an appendix (tables A-1 through A-4). All other emission data are reported as averages for each type of engine tested. This method of reporting the data was chosen because an insufficient number of tests precluded a meaningful statistical presentation, either as a means of showing data variability for a particular type of engine or for comparison of emissions among the different types. The figures and tables containing average values are, therefore, not intended to define slight differences between data points, but to present a broad picture of test results so that larger differences can be readily distinguished.

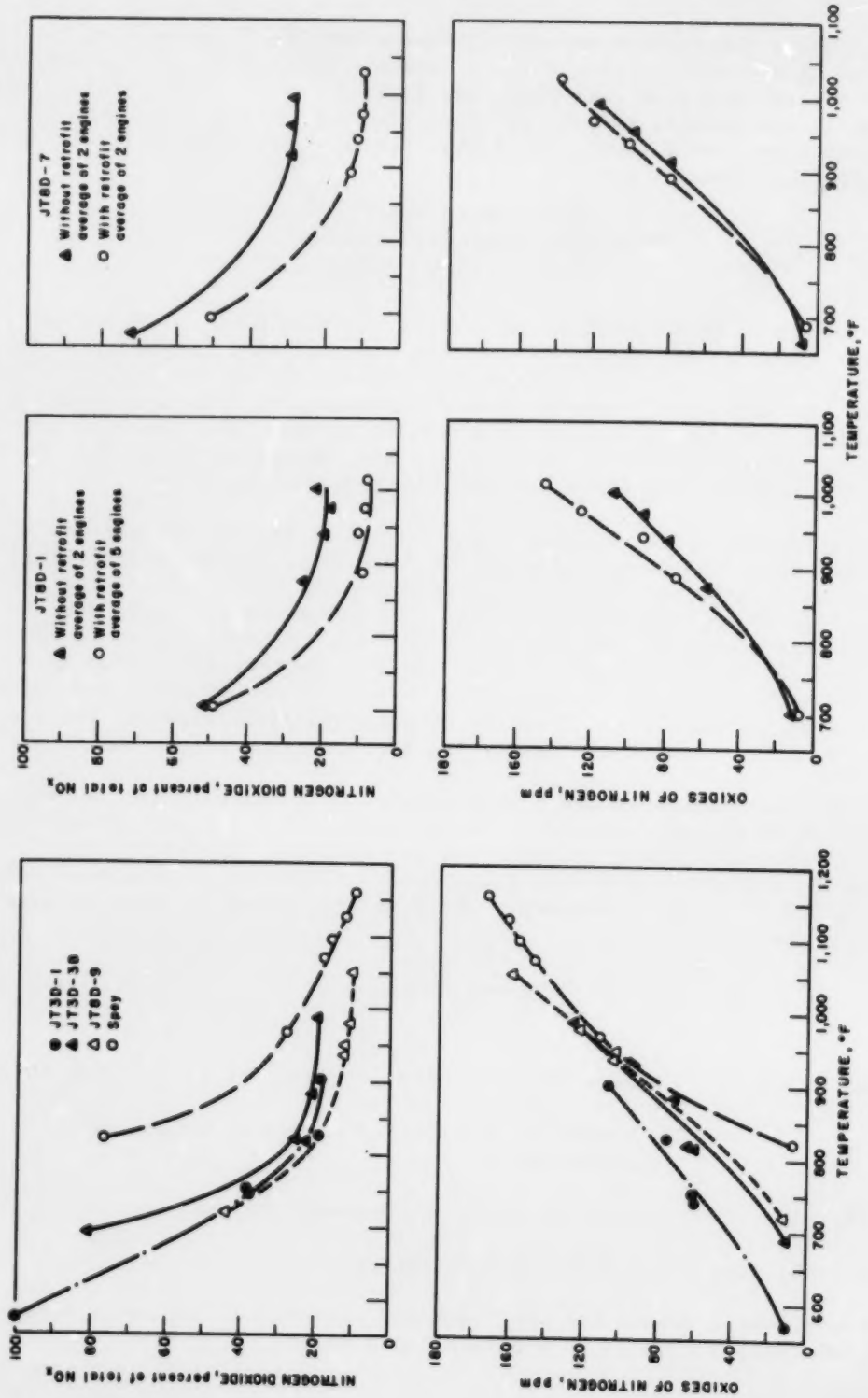

FIGURE 5. - Oxides of Nitrogen and Nitrogen Dioxide as a Function of Exhaust Gas Temperature.

Table 3 shows the average exhaust concentrations for each mode of the various types of aircraft turbine engines tested. Shown also are the averages of observed thrust, observed fuel flow, and fuel-air ratio (F/A). The values for the exhaust components, thrust, and fuel flow were measured and the F/A was calculated from the CO (ppm), CO_2 (pct), and HC (ppm) exhaust levels using the following approximation (3):

$$F/A \approx \frac{\frac{CO}{10^4} + CO_2 + \frac{HC}{10^4}}{207 - 2\left(\frac{CO}{10^4}\right) - CO_2} . \qquad (2)$$

NO_2 was definitely detected as an exhaust gas component, as shown in table 3. The trend of NO_2 emissions over the range of engine speeds was not as predictable nor as clearly defined as the pattern for NO (or NO_x) emissions. Spey engines, in particular, exhibited an interesting NO_2 emission trend, with maximum exhaust levels occurring at intermediate speeds. Too few JT3D engines were tested to establish the NO_2 pattern, but the concentration of this pollutant in JT8D exhaust definitely increased with engine speed.

One relationship which exhibits a similar trend for all three types of engines is NO_2 expressed as a percentage of total NO_x. Figure 5 shows this relationship as a function of exhaust gas temperature (EGT). Also, the corresponding plots of NO_x and EGT are shown. All values except those for the single JT3D-1 are averages. At low EGT (idle), NO_2 accounts for 45 to 100 pct of the NO_x content of the exhaust, but at higher temperatures (cruise to takeoff), the NO_2 portion of NO_x generally falls to 10 to 30 pct. Note also in figure 5 that the NO_x levels from the retrofitted JT8D, JT3D-3B, and Spey engines in the 950° F region are nearly the same, varying only about 10 pct.

Mass emissions represent the actual weights of pollutants emitted and are independent of exhaust dilution. Consequently, they are more indicative of pollution potential than are exhaust concentrations. Therefore, the average exhaust concentrations from table 3 were converted to pounds of pollutant per 1,000 lb of fuel consumed. These values, given in table 4, were obtained from the expression:

$$W_x \approx \frac{A_x\ (X)}{\frac{CO}{10^4} + CO_2 + \frac{HC}{10^4}} , \qquad (3)$$

in which W_x = mass emission rate of component X, lb/1,000 lb fuel,

A_x = constant, function of molecular weight of component X,

(X) = concentration of component X, ppm,

and CO, CO_2, and HC = exhaust concentrations.

The emission rates in pounds per hour were not calculated, but table 4 contains the information necessary to obtain these values.

TABLE 3. - Average of exhaust concentrations

Mode	Engine operating parameters			Components in wet exhaust					
	Thrust, lb	Fuel, lb/hr	Fuel-air ratio	CO, ppm	CO_2, pct	NO, ppm	NO_2, ppm	HC, ppmC	Aldehydes, ppm
JT3D-1 ENGINE (1 ONLY)									
Idle	930	900	0.0078	700.0	1.39	0.0	10.0	1,469.0	38.40
Part power (trim)	8,400	4,500	.0114	55.0	2.33	36.7	22.0	5.8	.92
Cruise	8,750	4,690	.0116	50.5	2.36	37.7	23.0	6.3	.65
Maximum continuous	11,610	6,390	.0123	29.2	2.52	60.6	14.0	4.3	.32
Takeoff	14,360	8,170	.0137	20.0	2.80	86.8	20.0	3.0	.31
JT3D-3B ENGINES (3)									
Idle	870	925	0.0076	750.0	1.31	1.9	8.0	1,674.0	38.95
Part power (trim)	10,955	5,950	.0114	26.4	2.33	47.7	16.5	4.4	.48
Cruise	10,875	5,895	.0114	31.0	2.33	47.6	13.5	4.7	.55
Maximum continuous	13,280	7,300	.0127	21.7	2.60	55.4	14.5	4.3	.40
Takeoff	15,900	9,185	.0143	18.3	2.91	[1]101.2	[1]24.5	[1]8.2	.31
JT8D-1 ENGINES WITHOUT RETROFIT (3)									
Idle	950	1,030	0.0028	122.3	0.52	3.6	4.7	49.7	4.33
Part power (trim)	9,240	5,410	.0086	30.7	1.76	38.8	[2]25.7	2.8	.21
Cruise	10,650	6,260	.0100	28.2	2.05	62.8	15.0	3.1	.26
Maximum continuous	11,690	6,905	.0105	26.5	2.14	75.1	16.0	2.6	.18
Takeoff	12,545	7,555	.0112	29.1	2.28	76.9	[3]37.8	2.7	.11
JT8D-1 ENGINES WITH RETROFIT (5)									
Idle	995	1,080	0.0041	130.4	0.83	3.9	3.6	46.9	4.37
Part power (trim)	9,185	5,445	.0100	19.8	2.06	66.6	6.3	2.0	.32
Cruise	10,540	6,260	.0109	16.8	2.23	82.2	9.0	2.5	.31
Maximum continuous	11,680	7,010	.0116	16.2	2.37	115.0	10.1	2.0	.35
Takeoff	12,450	7,480	.0122	16.5	2.49	132.5	11.0	1.8	.39
JT8D-7 ENGINES WITHOUT RETROFIT (2)									
Idle	1,025	1,075	0.0026	119.0	0.52	2.3	6.0	58.4	4.25
Part power (trim)[1]	9,750	5,740	.0099	29.0	2.02	47.2	24.0	1.7	.34
Cruise	10,860	6,400	.0106	26.7	2.17	57.1	23.3	6.2	.41
Maximum continuous	12,060	7,170	.0116	25.1	2.37	70.0	29.5	4.0	.56
Takeoff	13,055	7,885	.0126	25.1	2.58	84.6	34.5	2.7	.61
JT8D-7 ENGINES WITH RETROFIT (2)									
Idle	960	1,060	0.0031	86.1	0.63	3.9	4.0	38.1	-
Part power (trim)	9,755	5,705	.0101	16.3	2.08	69.7	10.8	2.6	-
Cruise	10,855	6,420	.0114	16.7	2.34	89.9	11.8	6.2	-
Maximum continuous	11,875	7,105	.0124	16.4	2.53	109.3	12.8	5.4	-
Takeoff	12,710	7,685	.0132	16.4	2.70	126.3	13.8	4.3	-
JT8D-9 ENGINES WITH RETROFIT (6)									
Idle	980	1,040	0.0038	115.5	0.80	6.5	5.1	68.5	4.72
Part power (trim)	10,485	6,095	.0115	21.4	2.36	90.2	12.4	2.5	.39
Cruise	10,830	6,310	.0117	20.3	2.38	89.7	12.4	4.5	.56
Maximum continuous	11,895	6,975	.0126	19.2	2.58	109.6	13.2	4.6	.47
Takeoff	13,570	8,200	.0140	17.8	2.85	142.7	14.6	5.1	.48
511-14 SPEY ENGINES (4)									
Idle	625	915	0.0067	632.0	1.16	1.8	5.9	742.8	34.18
Takeoff	11,140	7,370	.0147	35.2	3.01	155.6	16.5	4.0	.89
Checkpoint 1	10,705	7,005	.0141	35.5	2.88	142.1	19.6	3.3	.62
Checkpoint 2	10,140	6,545	.0135	36.7	2.75	130.0	24.8	3.0	.57
Checkpoint 3	9,575	6,145	.0130	37.7	2.65	121.0	26.6	3.0	.52
Checkpoint 4	7,490	4,685	.0114	44.8	2.32	80.0	30.3	2.8	.43

[1]One engine only.

[2]NO_2 level from one engine was extremely high. (Average of the two other engines is 14.0 ppm.)

[3]NO_2 level from one engine was extremely high. (Average of the two other engines is 22.8 ppm.)

TABLE 4. - Average of mass exhaust emissions

Mode	Engine operating parameters			Components, lb/1,000 lb fuel			
	Thrust, lb	Fuel, lb/hr	Fuel-air ratio	CO	NO_x	HC	Aldehydes
JT3D-1 ENGINE (1 ONLY)							
Idle	930	900	0.0078	87.1	2.0	91.4	5.1
Part power (trim)	8,400	4,500	.0114	4.7	8.3	.25	.08
Cruise	8,750	4,690	.0116	4.3	8.4	.27	.06
Maximum continuous	11,610	6,390	.0123	2.3	9.7	.17	.03
Takeoff	14,360	8,170	.0137	1.4	12.5	.11	.02
JT3D-3B ENGINES (3)							
Idle	870	925	0.0075	96.6	2.1	107.9	5.4
Part power (trim)	10,955	5,950	.0114	2.3	9.1	.19	.04
Cruise	10,875	5,895	.0114	2.7	8.6	.20	.05
Maximum continuous	13,280	7,300	.0127	1.7	8.8	.17	.03
Takeoff	15,900	9,185	.0143	1.3	[1]14.2	[1].28	.02
JT8D-1 ENGINES WITHOUT RETROFIT (3)							
Idle	950	1,030	0.0028	45.5	5.1	9.3	1.7
Part power (trim)	9,240	5,410	.0086	3.5	12.0	.16	.03
Cruise	10,650	6,260	.0100	2.7	12.5	.12	.02
Maximum continuous	11,690	6,905	.0105	2.5	14.0	.12	.02
Takeoff	12,545	7,555	.0112	2.5	16.5	.12	.01
JT8D-1 ENGINES WITH RETROFIT (5)							
Idle	995	1,080	0.0041	30.8	2.9	5.5	1.1
Part power (trim)	9,185	5,445	.0100	1.9	11.6	.10	.03
Cruise	10,540	6,260	.0109	1.5	13.4	.11	.03
Maximum continuous	11,680	7,010	.0116	1.4	17.4	.08	.03
Takeoff	12,450	7,480	.0122	1.3	18.9	.07	.03
JT8D-7 ENGINES WITHOUT RETROFIT (2)							
Idle	1,025	1,075	0.0026	44.2	5.1	10.9	1.7
Part power (trim)[1]	9,750	5,740	.0099	2.9	11.6	.08	.04
Cruise	10,860	6,400	.0106	2.5	12.2	.29	.04
Maximum continuous	12,060	7,170	.0116	2.1	13.8	.17	.05
Takeoff	13,055	7,885	.0126	1.9	15.2	.10	.03
JT8D-7 ENGINES WITH RETROFIT (2)							
Idle	960	1,060	0.0031	26.8	4.0	5.9	-
Part power (trim)	9,755	5,705	.0101	1.6	12.7	.12	-
Cruise	10,855	6,420	.0114	1.4	14.3	.26	-
Maximum continuous	11,875	7,105	.0124	1.3	15.9	.21	-
Takeoff	12,710	7,685	.0132	1.2	17.1	.16	-
JT8D-9 ENGINES WITH RETROFIT (6)							
Idle	980	1,040	0.0038	28.2	4.7	8.4	1.2
Part power (trim)	10,485	6,095	.0115	1.8	14.3	.11	.04
Cruise	10,830	6,310	.0117	1.7	14.1	.19	.05
Maximum continuous	11,895	6,975	.0126	1.5	15.6	.18	.04
Takeoff	13,570	8,200	.0140	1.2	18.1	.18	.04
511-14 SPEY ENGINES (4)							
Idle	625	915	0.0067	97.5	2.0	57.3	5.6
Takeoff	11,140	7,370	.0147	2.3	18.8	.13	.06
Checkpoint 1	10,705	7,005	.0141	2.4	18.1	.11	.05
Checkpoint 2	10,140	6,545	.0135	2.7	18.5	.11	.04
Checkpoint 3	9,575	6,145	.0130	2.8	18.3	.11	.04
Checkpoint 4	7,490	4,685	.0114	3.9	15.6	.12	.04

[1]One engine only.

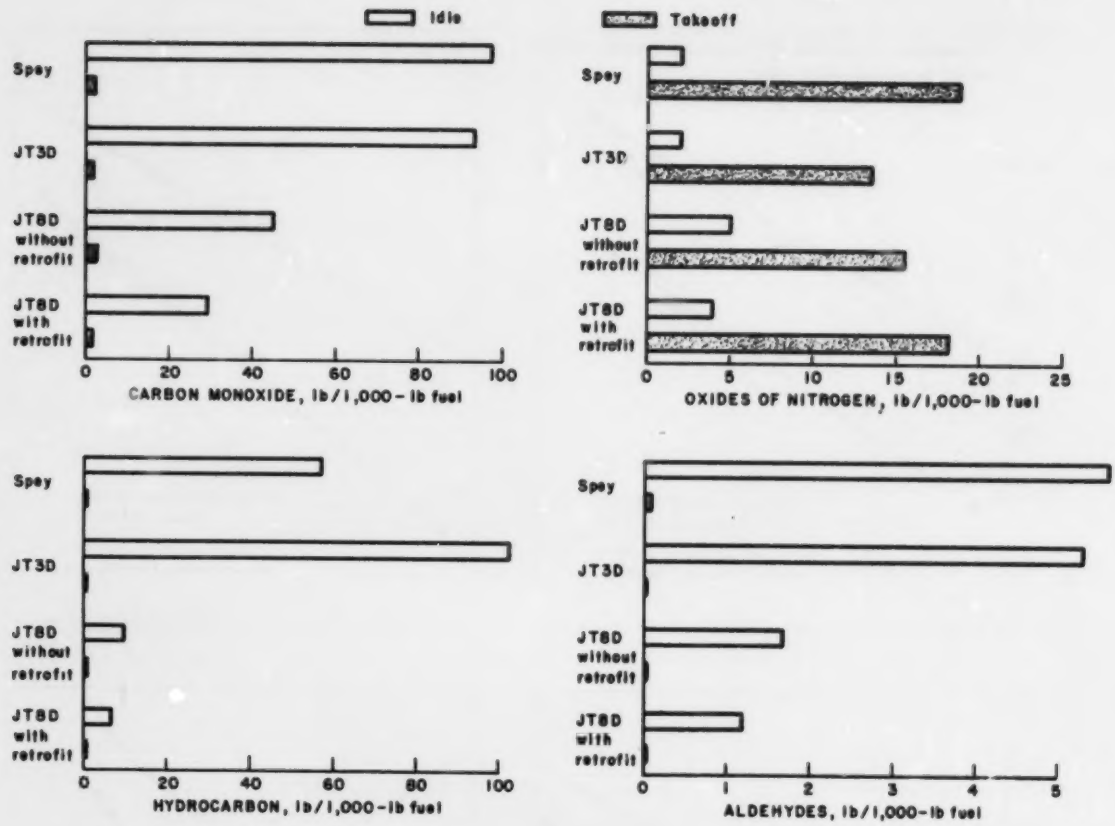

FIGURE 6. - Exhaust Emissions Averaged for Each Engine Type at Idle and Takeoff.

With engine speed increasing from idle to takeoff, the overall mass emission trends were (1) increasing NO_x and (2) decreasing CO, HC, and aldehyde emissions. Therefore, emission rates at idle and takeoff very nearly represent the emission limits for normally operating hot engines (excluding cold starts and malfunctions). A bar graph, figure 6, affords a convenient comparison of pollutant mass emitted by the various engine types. The values given are averages of all engines of each type tested.

When testing internal-bypass turbofan engines, an undetermined volume of air may be taken into the sample probe along with the exhaust gases. Low concentrations of exhaust components resulting from this mixing can be misleading. As stated previously, mass emissions calculated from exhaust levels by equation 3 are independent of dilution, but a certain amount of information can be gained from exhaust concentrations alone. Both JT8D and Spey engines are internal-bypass turbofans, and, to determine the extent of air-exhaust mixing, fuel-air ratios were plotted versus pounds of observed engine thrust (fig. 7). The F/A values for the B curves were taken from table 3, and the F/A values for the A curves were obtained from fuel flow and primary airflow. Airflows were obtained from standard average airflow curves provided by

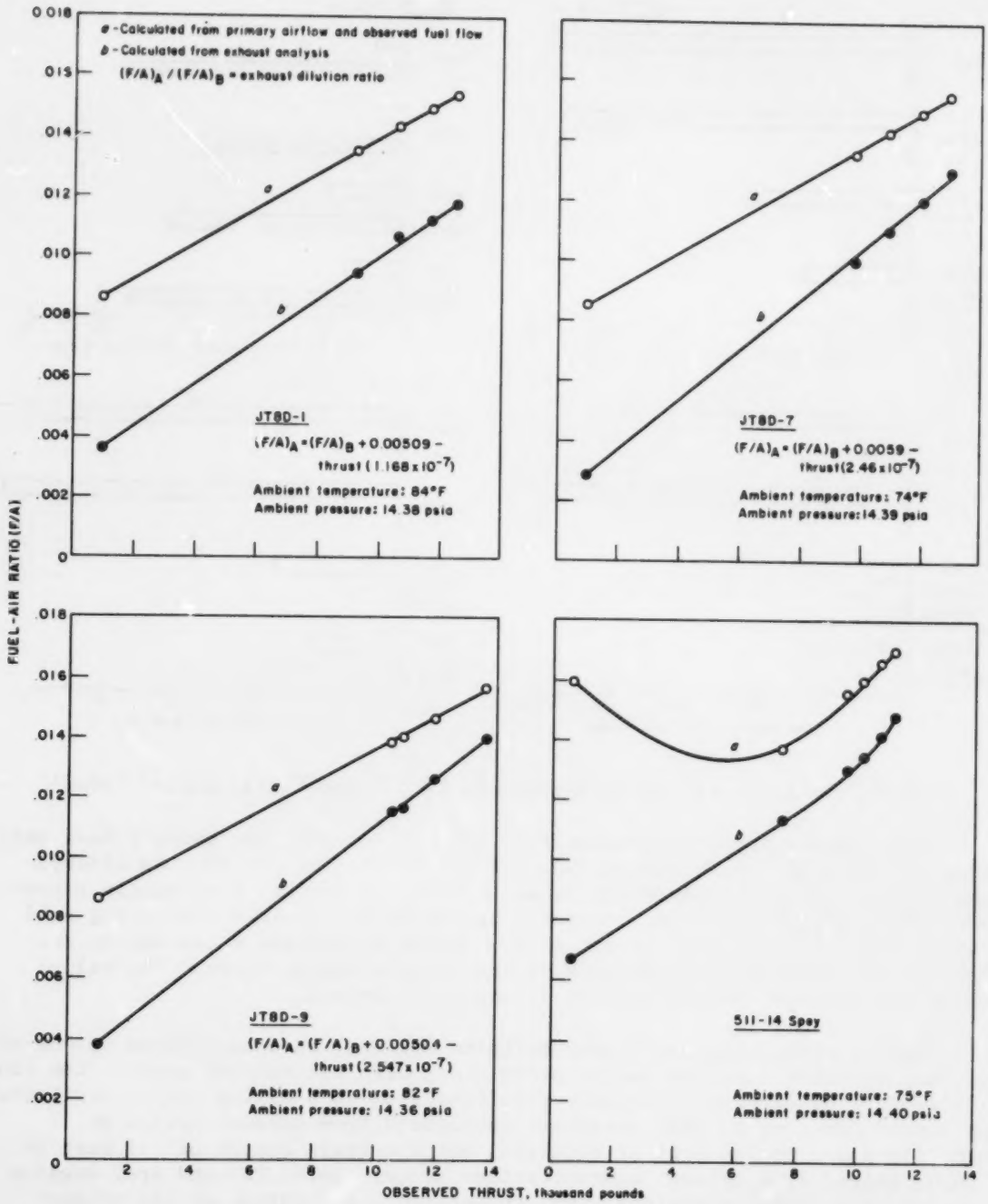
a - Calculated from primary airflow and observed fuel flow
b - Calculated from exhaust analysis
(F/A)A / (F/A)B = exhaust dilution ratio
JT8D-1
(F/A)A = (F/A)B + 0.00509 - thrust (1.168 x 10-7)
Ambient temperature: 84°F
Ambient pressure: 14.38 psia
JT8D-7
(F/A)A = (F/A)B + 0.0059 - thrust (2.46 x 10-7)
Ambient temperature: 74°F
Ambient pressure: 14.39 psia
JT8D-9
(F/A)A = (F/A)B + 0.00504 - thrust (2.547 x 10-7)
Ambient temperature: 82°F
Ambient pressure: 14.36 psia
511-14 Spey
Ambient temperature: 75°F
Ambient pressure: 14.40 psia
FUEL-AIR RATIO (F/A)
OBSERVED THRUST, thousand pounds

FIGURE 7. - Fuel-Air Ratio as a Function of Thrust.

American Airlines. If no air-exhaust mixing had occurred, curves A and B for each engine type would have been nearly superimposed. It is apparent from

figure 7 that (1) mixing occurred over the entire thrust range and (2) the exhaust dilution ratio was inversely proportional to the thrust. Equations for correcting curve B to curve A were derived from the simultaneous solution of their point-slope formulas. These formulas show that the rate change of F/A indicated by exhaust concentrations is nearly the same for JT8D-7 and JT8D-9 engines, but considerably different for JT8D-1 engines. The exhaust dilution ratios, given by $(F/A)_A$ divided by $(F/A)_B$, can be used to show the extent of air-exhaust mixing at a particular thrust value and to estimate actual exhaust component levels for JT8D and Spey engines from those given in table 3 and appendix A.

A similar F/A analysis was applied to the JT3D engines. The results were as follows:

Mode	A	B	Percent deviation $[(B - A) \cdot 100]/A$
Part power.....	0.0108	0.0114	+5.8
Cruise.....	.0108	.0115	+6.2
Maximum continuous...	.0119	.0126	+5.5
Takeoff.....	.0134	.0141	+5.5

Column A contains the F/A values obtained from fuel flow and primary airflow, and column B, the F/A values taken from table 3. Because JT3D engines are external-bypass turbofans, A and B values should be identical. The slight difference between the two sets of values may be due to testing an insufficient number of engines or deviation of the actual airflow from standard values.

SUMMARY

Exhaust emissions were measured from 25 aircraft turbine engines representative of the American Airlines fleet using Jet A fuel. The measurements were made at the American Airlines overhaul facility as routine acceptance tests were performed. The engine operating modes were those in routine use by American Airlines.

Analytical instrumentation was in accordance with SAE recommendations contained in ARP 1256. Levels of CO, CO_2, NO, NO_2, and HC were determined by following the SAE analytical procedure as closely as field conditions allowed. Grab samples were taken for aldehyde analysis by the MBTH method.

CO and aldehyde emissions were highest for the Spey engines and lowest for the JT8D engines. HC emission was highest for the JT3D engines and lowest for the JT8D engines. NO_x emission, slightly lower for the JT3D engines, showed the least amount of variation.

JT8D engines retrofitted with smoke-reducing burner cans exhibited lower CO, HC, and aldehyde emissions but slightly higher NO_x emissions.

NO_2 constituted 45 to 100 pct of total NO_x at low engine speeds and 10 to 30 pct at speeds approaching takeoff.

Fuel-air ratio was calculated from fuel flow and primary airflow and from exhaust component concentrations for the JT8D and Spey engines. A comparison of these two methods of calculation showed high secondary air-exhaust dilution at idle but less dilution at higher thrust. This mixing of secondary air and exhaust at the sample probe results in lower recorded component concentrations but does not affect computation of mass emission rates.

Probe failure was probably the most serious problem encountered. The initial probe design was inadequate for any of the engine types tested, and the final probe design could not withstand the exhaust temperatures and pressures generated by JT3D and Spey engines. Less severe problems encountered included temperature control of sample line and failures of probe support stands.

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APPENDIX.--INDIVIDUAL TEST DATA

TABLE A-1. - One JT3D-1, three JT3D-3B, and three JT8D-1 engines

	JT3D-1	JT3D-3B			JT8D-1		
Engine serial No.	642590	[1]667944	645643	645361	653301	649131	653435
Test date	7-21-71	7-29-71	7-29-71	8-4-71	7-12-71	7-19-71	8-3-71
TEST PARAMETERS							
Total time on engine, hr	21,605	9,380	11,176	12,283	11,982	14,443	11,614
Hours since:							
Hot-section overhaul	0	2,931	161	1,968	3,181	3,948	7,277
N_1 compressor overhaul	0	9,380	11,176	1,968	0	5,712	11,614
N_2 compressor overhaul	0	9,380	5,192	1,968	3,181	5,712	11,614
Combustor can replacement	0	-	-	1,968	3,181	3,948	7,277
First-stage nozzle-guide vane overhaul	0	2,931	5,192	1,968	3,181	3,948	2,768
N_1 turbine overhaul	0	9,380	11,176	1,968	0	3,948	2,768
N_2 turbine overhaul	0	9,380	11,176	1,968	0	3,948	11,614
Inlet air temperature, ° F:							
Start of test	85	74	67	83	95	78	75
End of test	-	-	68	90	96	78	76
Atmospheric pressure, psia:							
Start of test	14.38	14.38	14.41	14.38	14.35	14.41	14.36
End of test	14.38	-	14.41	14.38	14.35	14.41	14.36
Relative humidity, pct	27	78	78	42	42	51	76
Inlet air humidity, ratio, lb-water/lb-air	0.008	0.014	0.012	0.013	0.015	0.010	0.014
ENGINE OPERATING PARAMETERS							
Clock time:							
Idle	1:35	1:15	10:30	6:35	4:00	2:40	10:35
Part power (trim)	1:30	-	10:20	6:30	4:05	2:35	10:30
Cruise	1:45	-	10:45	6:05	4:15	2:20	-
Maximum continuous	1:50	-	10:50	6:10	4:20	2:25	-
Takeoff	2:00	-	10:55	6:45	4:25	2:30	10:45
Thrust (observed), lb:							
Idle	930	600	950	790	870	1,030	950
Part power (trim)	8,400	-	11,310	10,600	8,760	9,410	9,550
Cruise	8,750	-	10,900	10,850	10,340	10,960	-
Maximum continuous	11,610	-	13,410	13,150	11,330	12,050	-
Takeoff	14,360	-	16,000	15,800	12,150	12,790	12,700
Engine speed, N_1:							
Idle	1,950	1,720	1,960	1,840	2,834	2,120	2,900
Part power (trim)	5,218	-	5,760	5,710	7,200	7,205	7,300
Cruise	5,270	-	5,700	5,760	7,596	7,539	-
Maximum continuous	5,876	-	6,150	6,190	7,805	7,786	-
Takeoff	6,370	-	6,670	6,700	8,005	7,970	8,060
Engine speed, N_2:							
Idle	5,592	5,140	5,650	5,460	7,052	7,198	7,180
Part power (trim)	8,947	-	9,280	9,320	11,029	11,040	11,030
Cruise	8,980	-	9,250	9,360	11,310	11,248	-
Maximum continuous	9,410	-	9,560	9,660	11,510	11,449	-
Takeoff	9,750	-	9,920	9,970	11,654	11,580	11,530
Measured fuel flow, lb/hr:							
Idle	900	1,000	960	890	1,065	980	1,030
Part power (trim)	4,500	-	6,048	5,850	5,290	5,310	5,630
Cruise	4,690	-	5,770	6,020	6,260	6,260	-
Maximum continuous	6,390	-	7,210	7,390	6,860	6,950	-
Takeoff	8,170	-	9,100	9,270	7,440	7,410	7,810
Fuel-air ratio:[2]							
Idle	0.0078	0.0067	0.0075	0.0076	0.0025	0.0036	0.0023
Part power (trim)	.0114	-	.0113	.0115	.0086	.0083	.0088
Cruise	.0116	-	.0113	.0115	.0101	.0099	-
Maximum continuous	.0123	-	.0125	.0130	.0104	.0106	-
Takeoff	.0137	-	.0139	.0147	.0109	.0111	.0116
Exhaust gas temperature, ° F:							
Idle	570	587	550	825	700	700	695
Part power (trim)	740	-	790	845	870	875	870
Cruise	750	-	775	855	935	940	-
Maximum continuous	825	-	845	920	970	975	-
Takeoff	900	-	940	1,030	1,000	1,005	1,000

See footnotes at end of table.

TABLE A-1. - One JT3D-1, three JT3D-3B, and three JT8D-1 engines--Continued

	JT3D-1	JT3D-3B			JT8D-1		
Engine serial No.	642590	[1]667944	645643	645361	653301	649131	653435
Test date	7-21-71	7-29-71	7-29-71	8-4-71	7-12-71	7-19-71	8-3-71
ENGINE OPERATING PARAMETERS--Continued							
Inlet air pressure, psia:							
Idle	14.36	-	14.37	14.34	14.33	14.33	-14.34
Part power (trim)	13.98	-	13.90	13.88	14.20	14.18	14.21
Cruise	13.97	-	13.92	13.77	14.18	14.14	-
Maximum continuous	13.83	-	13.91	13.77	14.17	14.13	-
Takeoff	13.72	-	13.71	13.71	14.16	14.14	14.14
Exhaust gas pressure, psia:							
Idle	14.92	14.63	14.66	14.63	14.90	14.99	15.95
Part power (trim)	18.44	-	20.79	20.07	22.55	23.17	23.19
Cruise	18.68	-	20.49	20.26	24.35	25.10	-
Maximum continuous	20.88	-	22.60	22.27	25.65	26.35	-
Takeoff	23.25	-	25.60	25.07	26.55	27.35	27.28
Engine pressure ratio:							
Idle	1.04	-	1.02	1.02	1.04	1.04	1.11
Part power (trim)	1.32	-	1.50	1.45	1.58	1.63	1.63
Cruise	1.34	-	1.47	1.47	1.72	1.78	-
Maximum continuous	1.50	-	1.62	1.62	1.81	1.86	-
Takeoff	1.70	-	1.87	1.83	1.87	1.93	1.93
EXHAUST ANALYSIS[3]							
Carbon monoxide, ppm:							
Idle	700.0	1,090.0	735.0	765.0	109.0	153.0	105.0
Part power (trim)	55.0	-	21.5	31.2	25.5	32.2	34.2
Cruise	50.5	-	33.3	28.7	27.2	29.2	-
Maximum continuous	29.2	-	22.0	21.3	26.2	26.8	-
Takeoff	20.0	-	16.5	20.0	27.2	27.2	33.0
Carbon dioxide, ppm:							
Idle	1.39	0.98	1.32	1.29	0.49	0.60	0.46
Part power (trim)	2.33	-	2.31	2.35	1.77	1.70	1.80
Cruise	2.36	-	2.31	2.35	2.07	2.02	-
Maximum continuous	2.52	-	2.55	2.65	2.12	2.16	-
Takeoff	2.80	-	2.83	2.99	2.22	2.26	2.37
Nitric oxide, ppm:							
Idle	0.0	1.9	1.4	2.3	4.9	3.9	2.1
Part power (trim)	36.7	-	50.2	45.1	43.5	42.9	30.0
Cruise	37.7	-	48.3	46.8	66.7	58.9	-
Maximum continuous	60.6	-	68.5	42.2	77.4	72.7	-
Takeoff	86.8	-	-	101.2	87.6	81.9	61.2
Nitrogen dioxide, ppm:							
Idle	10.0	4.0	6.0	10.0	3.0	6.0	5.0
Part power (trim)	22.0	-	10.0	23.0	10.0	18.0	[4]49.0
Cruise	23.0	-	10.0	17.0	15.0	15.0	-
Maximum continuous	14.0	-	11.0	18.0	17.0	15.0	-
Takeoff	20.0	-	-	24.5	21.5	24.0	[4]68.0
Hydrocarbon, ppmC:							
Idle	1,469.0	2,959.0	1,469.0	1,878.0	47.5	64.8	36.7
Part power (trim)	5.8	-	2.8	6.0	3.5	2.2	2.6
Cruise	6.3	-	3.0	6.3	3.0	3.2	-
Maximum continuous	4.3	-	2.2	6.3	2.6	2.6	-
Takeoff	3.0	-	-	8.2	3.0	2.2	2.8
Aldehydes, ppm:							
Idle	38.40	56.7	37.20	40.7	3.38	5.28	-
Part power (trim)	.92	-	.56	.39	.25	.17	-
Cruise	.65	-	.47	.62	.26	.25	-
Maximum continuous	.32	-	.28	.51	.12	.24	-
Takeoff	.31	-	.15	.46	.07	.14	-

[1]Untrimmed idle only.
[2]Calculated from exhaust gas analysis.
[3]Measured on wet basis excepting nitric oxide, which was measured dry and converted to wet basis.
[4]Exceptionally high values.

TABLE A-2. - Five JT8D-1 engines with retrofit and two JT8D-7 engines

Engine serial No.	JT8D-1 with retrofit					JT8D-7	
	654458	649416	648920	648822	653304	654462	654992
Test date	7-14-71	7-16-71	7-20-71	7-21-71	7-28-71	7-28-71	7-29-71
TEST PARAMETERS							
Total time on engine, hr	8,340	12,536	15,449	14,661	13,257	9,898	5,804
Hours since:							
Hot-section overhaul	0	0	0	0	0	4,917	2,161
N_1 compressor overhaul	2,030	2,160	0	0	6,390	9,898	5,804
N_2 compressor overhaul	0	0	0	0	6,390	9,898	5,804
Combustor can replacement	0	0	0	0	0	4,917	2,161
First-stage nozzle-guide vane overhaul	0	0	0	0	0	3,718	2,161
N_1 turbine overhaul	3,099	0	0	0	0	4,917	5,804
N_2 turbine overhaul	0	0	0	0	0	9,898	5,804
Inlet air temperature, ° F:							
Start of test	98	79	78	89	81	73	67
End of test	99	78	79	90	-	73	68
Atmospheric pressure, psia:							
Start of test	14.35	14.35	14.45	14.35	14.38	14.32	14.39
End of test	14.35	14.35	14.45	14.35	14.38	14.32	14.39
Relative humidity, pct	30	65	34	27	61	79	78
Inlet air humidity, ratio, lb-water/lb-air	0.013	0.011	0.008	0.009	0.009	0.014	0.011
ENGINE OPERATING PARAMETERS							
Clock time:							
Idle	1:00	1:00	11:50	3:20	4:15	10:10	8:45
Part power (trim)	1:05	12:55	12:05	-	4:10	9:55	-
Cruise	1:15	1:25	11:30	3:45	4:20	10:15	8:20
Maximum continuous	1:20	-	11:35	3:50	4:25	10:20	8:25
Takeoff	1:25	-	11:45	3:55	4:30	10:30	8:35
Thrust (observed), lb:							
Idle	970	990	1,040	970	990	1,000	1,050
Part power (trim)	8,580	9,400	9,610	-	9,150	9,750	-
Cruise	10,110	10,800	10,900	10,080	10,800	10,940	10,780
Maximum continuous	11,130	-	11,980	11,640	11,960	12,060	12,060
Takeoff	12,020	-	12,760	12,450	12,570	12,960	13,150
Engine speed, N_1:							
Idle	2,948	2,910	2,980	-	2,120	2,900	2,950
Part power (trim)	7,177	7,215	7,280	-	7,190	7,275	-
Cruise	7,534	7,510	7,600	-	7,580	7,530	7,490
Maximum continuous	7,773	-	7,850	-	7,860	7,780	7,800
Takeoff	7,984	-	8,035	-	8,010	7,990	8,070
Engine speed, N_2:							
Idle	7,275	7,200	7,310	7,225	7,170	7,150	7,240
Part power (trim)	11,055	10,980	11,000	-	10,880	11,060	-
Cruise	11,340	11,200	11,200	11,165	11,200	11,250	11,130
Maximum continuous	11,548	-	11,410	11,410	11,400	11,480	11,360
Takeoff	11,687	-	11,560	11,535	11,520	11,620	11,540
Measured fuel flow, lb/hr:							
Idle	1,133	1,063	1,068	1,060	1,075	1,110	1,040
Part power (trim)	5,190	5,540	5,590	-	5,460	5,740	-
Cruise	6,150	6,450	6,410	5,930	6,360	6,520	6,280
Maximum continuous	6,770	-	7,090	7,050	7,120	7,230	7,110
Takeoff	7,410	-	7,630	7,270	7,610	7,860	7,910
Fuel-air ratio:[1]							
Idle	0.0035	0.0058	0.0034	0.0046	0.0032	0.0027	0.0026
Part power (trim)	.0097	.0109	.0099	-	.0097	.0099	-
Cruise	.0097	.0118	.0111	.0110	.0111	.0113	.0099
Maximum continuous	.0101	-	.0119	.0122	.0120	.0124	.0107
Takeoff	.0107	-	.0127	.0126	.0127	.0133	.0119
Exhaust gas temperature, ° F:							
Idle	735	715	670	730	655	710	620
Part power (trim)	900	900	875	-	875	910	-
Cruise	960	945	920	940	940	960	865
Maximum continuous	990	-	955	995	970	1,000	910
Takeoff	1,020	-	990	1,050	995	1,035	950

See footnotes at end of table.

TABLE A-2. - Five JT8D-1 engines with retrofit and two JT8D-7 engines--Continued

	JT8D-1 with retrofit					JT8D-7	
Engine serial No.	654458	649416	648920	648822	653304	654462	654992
Test date	7-14-71	7-16-71	7-20-71	7-21-71	7-28-71	7-28-71	7-29-71
ENGINE OPERATING PARAMETERS--Continued							
Inlet air pressure, psia:							
Idle	14.33	14.33	14.43	14.33	14.36	14.30	14.37
Part power (trim)	14.20	14.15	14.36	-	14.20	14.15	-
Cruise	14.19	14.15	14.38	14.19	14.17	14.14	14.33
Maximum continuous	14.18	-	14.37	14.13	14.16	14.10	14.17
Takeoff	14.17	-	14.36	14.12	14.15	14.07	14.16
Exhaust gas pressure, psia:							
Idle	15.6	14.75	15.05	14.99	14.97	14.81	14.98
Part power (trim)	30.7	23.10	23.43	-	22.71	23.49	-
Cruise	34.4	24.65	25.05	23.95	24.24	24.92	25.01
Maximum continuous	37.1	-	26.35	25.88	26.36	26.27	26.54
Takeoff	39.2	-	27.35	26.85	27.20	27.37	27.93
Engine pressure ratio:							
Idle	1.01	1.03	1.0	1.04	1.04	1.04	1.04
Part power (trim)	2.12	1.63	1.63	-	1.60	1.67	-
Cruise	2.36	1.74	1.74	1.69	1.64	1.76	1.75
Maximum continuous	2.54	-	1.83	1.83	1.85	1.86	1.87
Takeoff	2.69	-	1.90	1.90	1.92	1.94	1.97
EXHAUST ANALYSIS[2]							
Carbon monoxide, ppm:							
Idle	87.0	169.0	101.0	188.0	107.0	131.0	107.0
Part power (trim)	19.5	19.5	20.5	-	19.5	29.0	-
Cruise	18.2	19.5	16.5	14.0	16.0	33.2	20.2
Maximum continuous	18.2	-	17.5	13.5	15.5	34.2	16.0
Takeoff	19.5	-	17.5	14.0	15.0	36.2	14.0
Carbon dioxide, ppm:							
Idle	0.71	1.17	0.69	0.93	0.65	0.53	0.51
Part power (trim)	1.98	2.23	2.03	-	1.98	2.02	-
Cruise	1.98	2.41	2.26	2.24	2.26	2.31	2.02
Maximum continuous	2.07	-	2.44	2.49	2.46	2.54	2.19
Takeoff	2.19	-	2.59	2.57	2.59	2.72	2.44
Nitric oxide, ppm:							
Idle	4.1	5.5	5.1	2.2	2.4	3.9	0.7
Part power (trim)	56.5	69.8	79.1	-	60.8	47.2	-
Cruise	90.0	43.7	101.8	90.5	85.0	56.2	58.0
Maximum continuous	108.0	-	124.1	122.6	105.4	67.1	72.9
Takeoff	130.0	-	144.9	136.7	118.5	78.5	90.6
Nitrogen dioxide, ppm:							
Idle	3.0	7.0	0.8	5.0	2.0	7.0	5.0
Part power (trim)	8.5	9.0	1.8	-	6.0	24.0	-
Cruise	9.0	8.5	8.5	10.5	8.5	40.0	6.5
Maximum continuous	10.0	-	9.0	12.0	9.5	51.0	8.0
Takeoff	11.0	-	10.0	13.0	10.0	60.0	9.0
Hydrocarbon, ppmC:							
Idle	24.2	64.8	47.5	46.4	51.8	67.0	49.7
Part power (trim)	2.2	1.9	1.7	-	2.2	1.7	-
Cruise	1.7	3.0	4.3	1.7	1.9	1.5	10.8
Maximum continuous	1.6	-	1.7	2.6	1.9	1.5	6.5
Takeoff	1.3	-	1.3	2.8	1.9	1.5	3.9
Aldehydes, ppm:							
Idle	2.71	6.36	4.15	4.53	4.10	4.25	-
Part power (trim)	.26	.36	.32	-	.33	.34	-
Cruise	.23	.29	.35	-	.35	.41	-
Maximum continuous	.27	-	.45	-	.32	.56	-
Takeoff	.36	-	.41	-	.41	.61	-

[1]Calculated from exhaust gas analysis.
[2]Measured on wet basis excepting nitric oxide, which was measured dry and converted to wet basis.

TABLE A-3. - Two JT8D-7 and six JT8D-9 engines with retrofit

	JT8D-7 with retrofit		JT8D-9 with retrofit					
Engine serial No.	654133	654374	665397	665281	665314	665166	665401	665359
Test date	7-30-71	8-2-71	6-23-71	6-25-71	7-22-71	7-26-71	7-27-71	7-28-71
TEST PARAMETERS								
Total time on engine, hr	9,583	10,486	5,469	6,589	6,766	7,361	0	6,077
Hours since:								
Hot-section overhaul	0	0	0	0	0	1,986	0	0
N_1 compressor overhaul	0	0	5,469	6,589	0	2,853	0	6,077
N_2 compressor overhaul	0	0	0	0	0	3,894	0	0
Combustor can replacement	0	0	0	0	0	1,986	0	0
First-stage nozzle-guide vane overhaul	0	0	0	6,589	0	1,986	0	0
N_1 turbine overhaul	7,003	0	0	6,589	6,766	5,001	6,681	6,077
N_2 turbine overhaul	0	0	0	0	-	5,372	7,641	0
Inlet air temperature, ° F:								
Start of test	74	80	85	90	83	72	79	81
End of test	75	-	86	91	82	72	81	-
Atmospheric pressure, psia:								
Start of test	14.48	14.38	14.35	14.35	14.30	14.40	14.38	14.38
End of test	14.48	-	14.33	14.35	14.30	14.40	14.38	14.38
Relative humidity, pct	54	53	52	42	65	76	67	76
Inlet air humidity, ratio, lb-water/lb-air	0.010	0.012	0.013	0.013	0.017	0.013	0.015	0.018
ENGINE OPERATING PARAMETERS								
Clock time:								
Idle	12:05	1:55	11:35	11:30	2:50	1:40	12:10	6:20
Part power (trim)	12:00	1:50	11:50	11:50	2:40	1:35	12:00	6:10
Cruise	12:10	2:05	12:15	11:45	2:55	1:50	12:20	6:25
Maximum continuous	12:15	2:15	12:25	11:40	3:00	1:55	12:30	6:30
Takeoff	12:20	2:20	12:35	11:35	3:05	2:00	12:35	6:35
Thrust (observed), lb:								
Idle	1,000	920	880	920	1,070	1,020	990	1,000
Part power (trim)	9,910	9,600	10,230	10,070	10,550	10,400	10,900	10,750
Cruise	10,860	10,850	10,800	10,600	10,870	10,900	10,900	10,900
Maximum continuous	12,000	11,750	11,840	11,640	11,890	12,000	12,000	12,000
Takeoff	13,300	12,120	13,610	13,360	13,440	13,700	13,720	13,580
Engine speed, N_1:								
Idle	2,890	2,890	2,770	2,890	2,990	2,900	2,890	2,900
Part power (trim)	7,380	7,300	7,360	7,377	7,430	7,360	7,440	7,450
Cruise	7,570	7,560	7,490	7,487	7,500	7,430	7,500	7,480
Maximum continuous	7,840	7,800	7,720	7,723	7,748	7,670	7,730	7,730
Takeoff	8,150	7,880	8,180	8,120	8,150	8,110	8,130	8,130
Engine speed, N_2:								
Idle	7,140	7,115	7,060	7,210	7,350	7,060	7,180	7,200
Part power (trim)	11,110	10,830	11,040	11,131	11,030	11,000	11,145	11,040
Cruise	11,270	11,025	11,160	11,217	11,050	10,900	11,160	11,040
Maximum continuous	11,500	11,230	11,310	11,384	11,255	11,130	11,350	11,260
Takeoff	11,730	11,275	11,620	11,590	11,520	11,410	11,620	11,510
Measured fuel flow, lb/hr:								
Idle	1,045	1,070	1,000	1,110	1,090	1,040	970	1,020
Part power (trim)	5,740	5,670	5,820	5,990	6,220	6,100	6,210	6,220
Cruise	6,380	6,460	6,200	6,340	6,440	6,330	6,220	6,340
Maximum continuous	7,120	7,090	6,880	7,040	7,130	6,960	6,880	6,970
Takeoff	8,060	7,310	8,190	8,300	8,290	8,210	8,110	8,110
Fuel-air ratio:[1]								
Idle	0.0026	0.0036	0.0051	0.0028	0.0031	0.0041	0.0038	0.0042
Part power (trim)	.0094	.0109	-	.0120	.0115	.0118	.0114	.0110
Cruise	.0105	.0123	.0118	.0121	.0113	.0119	.0117	.0111
Maximum continuous	.0115	.0133	.0131	.0138	.0120	.0128	.0126	.0114
Takeoff	.0127	.0137	.0144	.0151	.0133	.0144	.0141	.0126
Exhaust gas temperature, ° F:								
Idle	685	695	765	-	715	725	690	700
Part power (trim)	890	895	950	925	935	935	930	950
Cruise	930	945	965	935	950	935	935	955
Maximum continuous	970	970	1,000	975	975	960	970	990
Takeoff	1,075	980	1,060	1,040	1,030	1,020	1,035	1,100

See footnotes at end of table.

TABLE A-3. - Two JT8D-7 and six JT8D-9 engines with retrofit--Continued

	JT8D-7 with retrofit		JT8D-9 with retrofit					
Engine serial No.	654133	654374	665397	665281	665314	665166	665401	665359
Test date	7-30-71	8-2-71	6-23-71	6-25-71	7-22-71	7-26-71	7-27-71	7-28-71
ENGINE OPERATING PARAMETERS--Continued								
Inlet air pressure, psia:								
Idle	14.46	14.37	-	14.38	14.28	14.38	14.36	14.36
Part power (trim)	14.32	14.23	-	14.20	14.14	14.21	14.19	14.19
Cruise	14.31	14.21	-	14.20	14.13	14.21	14.19	14.16
Maximum continuous	14.29	14.20	-	14.20	14.08	14.19	14.18	14.14
Takeoff	14.29	14.20	-	14.20	14.08	14.17	14.16	14.11
Exhaust gas pressure, psia:								
Idle	15.12	14.97	15.30	15.20	14.88	14.99	15.02	14.87
Part power (trim)	23.85	23.44	24.50	23.30	24.40	24.40	24.78	24.68
Cruise	25.02	24.78	24.70	25.90	24.80	25.04	24.94	24.90
Maximum continuous	26.43	26.16	25.90	26.30	26.20	26.35	26.17	26.43
Takeoff	27.97	26.53	28.30	28.30	28.50	28.70	28.53	28.38
Engine pressure ratio:								
Idle	1.05	1.04	1.02	1.05	1.04	1.04	1.05	1.03
Part power (trim)	1.66	1.65	2.0[illegible]	1.63	1.73	1.72	1.75	1.74
Cruise	1.75	1.74	2.14	1.80	1.75	1.76	1.76	1.76
Maximum continuous	1.85	1.84	2.28	1.84	1.86	1.85	1.85	1.87
Takeoff	1.96	1.87	2.55	1.98	2.02	2.03	2.02	2.00
EXHAUST ANALYSIS[2]								
Carbon monoxide, ppm:								
Idle	76.2	96.0	137.0	66.0	120.0	158.0	107.0	105.0
Part power (trim)	13.0	19.5	-	28.0	18.0	23.0	19.2	19.0
Cruise	13.8	19.5	18.0	27.0	17.0	22.5	19.6	17.5
Maximum continuous	13.8	19.0	18.0	24.0	16.5	20.5	19.4	16.5
Takeoff	13.8	19.0	16.0	20.0	16.0	19.5	19.2	16.0
Carbon dioxide, ppm:								
Idle	0.53	0.73	1.02	0.56	0.80	0.82	0.77	0.85
Part power (trim)	1.93	2.22	-	2.45	2.36	2.42	2.33	2.24
Cruise	2.15	2.52	2.41	2.48	2.31	2.44	2.39	2.26
Maximum continuous	2.34	2.72	2.67	2.82	2.46	2.62	2.57	2.34
Takeoff	2.59	2.80	2.93	3.07	2.72	2.93	2.88	2.57
Nitric oxide, ppm:								
Idle	3.6	4.1	17.4	5.5	3.4	7.3	1.9	3.3
Part power (trim)	75.2	64.1	-	112.0	89.7	82.1	83.0	84.2
Cruise	93.4	86.4	97.6	118.0	106.0	43.3	85.6	87.8
Maximum continuous	114.6	103.9	121.0	138.0	117.2	69.3	103.4	108.6
Takeoff	142.9	109.6	170.0	167.0	157.2	70.0	149.3	142.4
Nitrogen dioxide, ppm:								
Idle	3.0	5.0	6.0	1.5	5.0	7.5	6.0	4.5
Part power (trim)	6.5	15.0	-	9.0	12.5	16.0	17.0	7.5
Cruise	5.5	18.0	6.0	9.0	14.0	19.0	18.0	8.5
Maximum continuous	6.0	19.5	8.0	8.5	14.0	19.0	20.0	9.5
Takeoff	8.0	19.5	12.0	7.5	16.0	21.0	21.0	10.0
Hydrocarbon, ppmC:								
Idle	34.6	41.5	108.0	-	58.3	90.7	51.8	33.7
Part power (trim)	2.6	2.6	-	-	2.2	3.9	1.5	2.4
Cruise	9.9	2.4	13.0	-	1.7	2.4	2.6	2.6
Maximum continuous	8.6	2.2	14.7	-	1.7	2.2	2.2	2.4
Takeoff	6.9	1.7	17.3	-	1.3	2.2	2.2	2.4
Aldehydes, ppm:								
Idle	-	-	4.39	2.76	4.98	7.14	4.34	-
Part power (trim)	-	-	-	.87	.23	.25	.1[illegible]	-
Cruise	-	-	-	1.59	.23	.23	.1[illegible]	-
Maximum continuous	-	-	-	1.22	.24	.24	.19	-
Takeoff	-	-	-	.90	.39	.36	.27	-

[1]Calculated from exhaust gas analysis.
[2]Measured on wet basis excepting nitric oxide, which was measured dry and converted to wet basis.

TABLE A-4. - Four 511-14 Spey engines

Engine serial No.	7071	7072	7072	8091	7065	7065
Test date	7-30-71	8-3-71	7-27-71	8-2-71	8-6-71	8-3-71
TEST PARAMETERS						
Total time on engine, hr	7,237	7,500	7,500	2,635	7,861	7,861
Hours since:						
Hot-section overhaul	0	0	0	0	658	658
N_1 compressor overhaul	1,635	7,500	7,500	2,130	7,861	7,861
N_2 compressor overhaul	1,635	7,500	7,500	2,130	7,861	7,861
Combustor can replacement	-	-	-	-	658	658
First-stage nozzle-guide vane overhaul	0	0	0	0	658	658
N_1 turbine overhaul	1,635	7,500	7,500	0	1,895	7,861
N_2 turbine overhaul	1,635	7,500	7,500	0	1,895	7,861
Inlet air temperature, ° F:						
Start of test	72	73	79	79	72	79
End of test	74	73	79	79	72	79
Atmospheric pressure, psia:						
Start of test	14.45	14.36	14.32	14.38	14.42	14.38
End of test	14.45	14.36	14.32	14.38	14.42	14.38
Relative humidity, pct	54	71	67	53	84	60
Inlet air humidity, ratio, lb-water/lb-air	0.007	0.013	0.014	0.011	0.015	0.013
ENGINE OPERATING PARAMETERS						
Clock time:						
Idle	1:25	10:25	10:20	3:05	9:50	2:25
Takeoff	1:00	10:00	-	2:35	9:25	1:55
Checkpoint No. 1	1:05	10:05	-	2:45	9:30	2:00
Checkpoint No. 2	1:10	10:10	-	2:50	9:35	2:10
Checkpoint No. 3	1:15	10:15	-	2:55	9:40	2:15
Checkpoint No. 4	1:20	10:20	-	3:00	9:45	2:20
Thrust (observed), lb:						
Idle	600	610	520	630	650	630
Takeoff	11,360	11,000	-	10,920	11,340	11,090
Checkpoint No. 1	10,820	10,500	-	10,500	10,900	10,800
Checkpoint No. 2	10,350	9,980	-	9,950	10,300	10,120
Checkpoint No. 3	9,830	9,300	-	9,430	9,800	9,510
Checkpoint No. 4	7,500	7,480	-	7,470	7,500	7,500
Engine speed, N_1:						
Idle	2,710	2,670	2,680	2,720	2,700	2,700
Takeoff	8,460	8,420	-	8,480	8,500	8,500
Checkpoint No. 1	8,280	8,260	-	8,330	8,380	8,390
Checkpoint No. 2	8,150	8,110	-	8,170	8,190	8,200
Checkpoint No. 3	8,020	7,940	-	8,010	8,050	8,030
Checkpoint No. 4	7,340	7,390	-	7,400	7,375	7,420
Engine speed, N_2:						
Idle	7,730	7,512	7,300	7,710	7,620	7,580
Takeoff	12,350	12,360	-	12,400	12,420	12,400
Checkpoint No. 1	12,200	12,210	-	12,290	12,320	12,360
Checkpoint No. 2	12,090	12,070	-	12,150	12,150	12,200
Checkpoint No. 3	11,980	11,900	-	12,010	12,000	12,040
Checkpoint No. 4	11,614	11,630	-	11,660	11,550	11,630

TABLE A-4. - Four 511-14 Spey engines--Continued

Engine serial No.....	7071	7072	7072	8091	7065	7065
Test date.....	7-30-71	8-3-71	7-27-71	8-2-71	8-6-71	8-3-71
ENGINE OPERATING PARAMETERS--Continued						
Measured fuel flow, lb/hr:						
Idle.....	920	900	1,130	890	930	930
Takeoff.....	7,620	7,280	-	7,070	7,480	7,370
Checkpoint No. 1.....	7,170	6,860	-	6,700	7,150	7,140
Checkpoint No. 2.....	6,800	6,480	-	6,200	6,670	6,570
Checkpoint No. 3.....	6,430	6,030	-	5,860	6,290	6,120
Checkpoint No. 4.....	4,800	4,710	-	4,510	4,690	4,720
Fuel-air ratio:[1]						
Idle.....	0.0051	0.0063	0.0075	0.0072	0.0066	0.0065
Takeoff.....	.0139	.0144	-	.0160	.0151	.0144
Checkpoint No. 1.....	.0131	.0137	-	.0156	.0147	.0135
Checkpoint No. 2.....	.0127	.0132	-	.0146	.0139	.0131
Checkpoint No. 3.....	.0122	.0124	-	.0142	.0137	.0126
Checkpoint No. 4.....	.0118	.0107	-	.0123	.0114	.0106
Exhaust gas temperature, ° F:						
Idle.....	825	830	850	800	820	820
Takeoff.....	1,170	1,160	-	1,140	1,155	1,165
Checkpoint No. 1.....	1,135	1,125	-	1,100	1,125	1,140
Checkpoint No. 2.....	1,110	1,100	-	1,075	1,100	1,100
Checkpoint No. 3.....	1,090	1,065	-	1,050	1,075	1,075
Checkpoint No. 4.....	975	975	-	945	955	970
Inlet air pressure, psia:						
Idle.....	14.44	14.35	-	14.37	14.41	14.37
Takeoff.....	14.23	14.14	-	14.15	14.19	14.16
Checkpoint No. 1.....	14.24	14.14	-	14.16	14.20	14.16
Checkpoint No. 2.....	14.24	14.15	-	14.18	14.20	14.17
Checkpoint No. 3.....	14.26	14.16	-	14.18	14.21	14.19
Checkpoint No. 4.....	14.28	14.20	-	14.22	14.25	14.21
Exhaust gas pressure, psia:						
Idle.....	15.43	15.10	-	15.26	15.30	22.72
Takeoff.....	36.45	35.40	-	35.28	35.98	35.58
Checkpoint No. 1.....	35.25	34.41	-	34.38	35.25	34.98
Checkpoint No. 2.....	34.30	33.18	-	33.26	34.03	33.52
Checkpoint No. 3.....	33.25	31.86	-	32.03	32.90	32.33
Checkpoint No. 4.....	28.41	28.10	-	27.38	28.24	28.13
Engine pressure ratio:						
Idle.....	1.07	1.05	-	1.06	1.06	1.59
Takeoff.....	2.56	2.50	-	2.49	2.54	2.51
Checkpoint No. 1.....	2.48	2.44	-	2.42	2.48	2.47
Checkpoint No. 2.....	2.40	2.34	-	2.35	2.40	2.36
Checkpoint No. 3.....	2.33	2.24	-	2.26	2.32	2.28
Checkpoint No. 4.....	1.99	1.98	-	1.92	1.98	1.98
EXHAUST ANALYSIS[2]						
Carbon monoxide, ppm:						
Idle.....	470.0	630.0	820.0	645.0	730.0	685.0
Takeoff.....	39.2	30.7	-	30.7	41.0	34.2
Checkpoint No. 1.....	38.2	30.7	-	32.3	43.0	33.2
Checkpoint No. 2.....	35.3	36.2	-	33.8	44.0	34.2
Checkpoint No. 3.....	35.3	37.7	-	34.3	46.0	35.3
Checkpoint No. 4.....	36.3	45.0	-	44.0	56.0	42.5

See footnotes at end of table.

TABLE A-4. - Four 511-14 Spey engines--Continued

Engine serial No.	7071	7072	7072	8091	7065	7065
Test date	7-30-71	8-3-71	7-27-71	8-2-71	8-6-71	8-3-71
EXHAUST ANALYSIS[2]--Continued						
Carbon dioxide, ppm:						
Idle	0.93	1.14	1.32	1.35	1.22	1.14
Takeoff	2.83	2.94	-	3.25	3.08	2.93
Checkpoint No. 1	2.67	2.80	-	3.18	3.00	2.76
Checkpoint No. 2	2.59	2.69	-	2.98	2.82	2.67
Checkpoint No. 3	2.49	2.53	-	2.90	2.78	2.57
Checkpoint No. 4	2.41	2.19	-	2.50	2.32	2.17
Nitric oxide, ppm:						
Idle	0.0	0.4	1.2	0.0	-	6.7
Takeoff	141.3	154.7	-	172.1	-	154.3
Checkpoint No. 1	125.1	141.2	-	158.2	-	143.9
Checkpoint No. 2	119.2	124.7	-	144.4	-	131.7
Checkpoint No. 3	112.6	118.6	-	130.7	-	122.0
Checkpoint No. 4	77.4	72.0	-	81.9	-	88.5
Nitrogen dioxide, ppm:						
Idle	6.5	6.0	3.0	8.0	6.0	3.0
Takeoff	9.0	18.0	-	29.0	18.0	8.5
Checkpoint No. 1	10.5	14.0	-	40.0	22.0	11.5
Checkpoint No. 2	11.0	28.0	-	43.0	29.0	13.0
Checkpoint No. 3	11.5	26.0	-	41.0	36.0	18.5
Checkpoint No. 4	11.0	55.0	-	36.0	33.0	16.5
Hydrocarbon, ppmC:						
Idle	659.0	851.0	1,296.0	734.0	620.0	850.0
Takeoff	-	4.0	-	4.5	5.0	2.5
Checkpoint No. 1	-	3.4	-	3.5	5.0	1.3
Checkpoint No. 2	-	3.1	-	3.0	4.0	2.0
Checkpoint No. 3	-	3.1	-	2.8	4.0	2.0
Checkpoint No. 4	-	3.4	-	2.6	3.0	2.0
Aldehydes, ppm:						
Idle	29.0	36.0	-	41.5	26.1	38.0
Takeoff	1.22	0.54	-	0.83	1.25	0.62
Checkpoint No. 1	.89	.50	-	.70	.66	.37
Checkpoint No. 2	.75	.53	-	.73	.46	.40
Checkpoint No. 3	.66	.48	-	.68	.48	.29
Checkpoint No. 4	.36	.48	-	.53	.44	.34

[1]Calculated from exhaust gas analysis.
[2]Measured on wet basis excepting nitric oxide, which was measured dry and converted to wet basis.

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